Reprinted from the *Soil Science Society of America Journal*
Volume 61, no. 5, Sept.–Oct. 1997
677 South Segoe Rd., Madison, WI 53711 USA

Particulate Organic Carbon Content and Potential Mineralization as Affected by Tillage and Texture

A. J. Franzluebbers and M. A. Arshad*

ABSTRACT

Conservation of soil organic carbon (SOC) is important for improving soil quality. Increasing the pool of particulate organic carbon (POC), thought to have a "slow" or medium turnover rate, with conservation tillage may be a critical step in improving the quality of agricultural soils. We determined the standing stock and potential mineralization rate of POC (defined as material >53 μm diam.) at depths of 0 to 50, 50 to 125, and 125 to 200 mm in four Boralfs (loam, silt loam, clay loam, and clay) under conventional shallow tillage (CT) and 4 to 16 yr of zero tillage (ZT) in northern Alberta and British Columbia. Standing stock of POC was consistently different between tillage regimes only at a depth of 0 to 50 mm, averaging 0.63 kg m^{-2} under CT and 0.76 kg m^{-2} under ZT. However, the ratio of specific POC mineralization to specific whole-SOC mineralization averaged 23% greater under ZT than under CT, suggesting that POC was of higher quality (i.e., more mineralizable) under ZT relative to other pools of SOC. With increasing clay content of the original soil, specific mineralization rate of POC increased after clay was removed by dispersion. This result suggests that clay may play an important role in sequestering POC by protecting its decomposition. Particulate organic C content was a more sensitive indicator of tillage-induced changes in SOC than the total amount of SOC. Zero tillage in this cold semiarid climate may increase both the active and slow pools of SOC within several years.

Soil organic matter is a critical component in maintaining the quality of agricultural soils (Doran et al., 1994). Soil management can have a varying influence on the total, microbial, and readily mineralizable pools of SOC depending on inherent site characteristics, including soil texture and climate (Collins et al., 1992; Gupta et al., 1994; Franzluebbers et al., 1994; Franzluebbers and Arshad, 1996a). The effects of climate and soil texture on SOC pools are not easily separated from the results in previous studies.

Particulate organic C, in addition to the more active pools of SOC, has been recently shown to be a sensitive indicator of soil management effects on SOC (Elliott et al., 1994). This fraction was considered to represent the "slow" pool of SOC (Cambardella and Elliott, 1992) with an intermediate turnover time between the "active" and "passive" pools (Parton et al., 1987). With a lignocellulose index of 43 to 50%, this pool of SOC represents an important intermediate decomposition stage of plant detritus that was rapidly lost following soil disturbance with cultivation (Cambardella and Elliott, 1992).

The effect of conservation tillage on the POC pool has not been consistent. Standing stock of POC under ZT was 36% greater than under stubble mulch at the end of 22 yr in a loam from Nebraska (Cambardella and Elliott, 1992), but not different between these tillage systems at the end of 25 yr in a silt loam from Colorado (Elliott et al., 1994). In only one of five comparisons between plowing and ZT on a silt loam in Kentucky and a silty clay loam in Indiana was the standing stock of POC significantly greater with ZT (Elliott et al., 1994). These studies on the effect of tillage regime on POC have been conducted on soil to a depth of 200 mm, yet the effect of tillage on more active pools of SOC has been shown to be limited to the surface 50 to 75 mm (Doran, 1987; Franzluebbers et al., 1994).

Although POC has been suggested to be a pool of SOC with an intermediate turnover time, little information exists on the actual decomposability of this fraction. Specific mineralization rates of several density fractions of POC were 5 to 33 times greater than from that from whole-SOC in Dutch grassland soils, with no apparent differences due to soil texture (Hassink, 1995a). In contrast, the specific mineralization rate of POC in several agricultural soils in Australia (Dalal and Mayer, 1986) and an agricultural soil in Canada (Gregorich et al., 1989) ranged from 0.9 to 1.5 times the specific mineralization rate of whole-SOC.

We investigated the effect of tillage regime on the depth distribution of POC and its specific mineralization in four soils varying in soil texture in the cold semiarid climate of northern Alberta and British Columbia.

A.J. Franzluebbers, USDA-ARS, Southern Piedmont Conservation Research Center, 1420 Experiment Station Road, Watkinsville, GA 30677; and M.A. Arshad, Agriculture and Agri-Food Canada, Northern Agriculture Research Centre, Box 29, Beaverlodge, Alberta T0H 0C0, Canada. Contribution from the Northern Agriculture Research Centre. Received 20 Aug. 1996. *Corresponding author (arshadc @em.agr.ca).

Published in Soil Sci. Soc. Am. J. 61:1382–1386 (1997).

Abbreviations: CT, conventional tillage; POC, particulate organic carbon; SOC, soil organic carbon; ZT, zero tillage.

MATERIALS AND METHODS

Soils managed under CT and ZT were collected from four locations in northern Alberta and British Columbia in late April to early May of 1995 prior to seeding. Specific location, soil characteristics, crop management, and experimental design are listed in Table 1. Mean annual temperature is 1 to 2°C and mean annual precipitation is 450 to 500 mm. Conventional tillage consisted of a cultivation (100–150-mm depth with 100-mm-wide chisels) after harvest followed by two cultivations (70–100-mm depth with 100-mm-wide chisels) in the spring prior to seeding. Zero tillage consisted of harrowing following harvest to evenly distribute straw and spraying glyphosate [isopropylamine salt of *N*-(phosphonomethyl) glycine] to control weeds prior to seeding. All crops were sown in mid May with a double-disk press drill in 170-mm-wide rows and harvested in September.

Soil samples consisted of eight soil cores (25-mm diam.) sectioned into depth increments of 0 to 50, 50 to 125, and 125 to 200 mm. Cores were collected in the center between rows of the previous crop and equidistantly along a diagonal transect within each plot. Soil was air dried and gently crushed to pass a 5.6-mm screen to remove large stones. Soil bulk density was calculated from an oven-dried subsample (60°C, 48 h) and the volume of the coring tool.

Particulate organic matter was determined with modifications to the method described by Cambardella and Elliott (1992). Soil (20 g) was dispersed in 100 mL of sodium hexametaphosphate (50 g L^{-1}) for 18 h with shaking by hand during the first 5 min and on a reciprocating shaker (90 cycles min^{-1}) during the final 2 h. The soil suspension was diluted to 1 L with distilled water for determination of clay content using a hydrometer at the end of 2 h (Gee and Bauder, 1986). The soil suspension was poured over a 53-μm screen. All material remaining on the screen, defined as the particulate organic fraction within a sand matrix, was washed into a drying dish, oven dried at 60°C for 24 h, and homogenized by passing through a 250-μm screen.

Organic C concentration of whole soil prior to fractionation (Franzluebbers and Arshad, 1996a,b) and of the particulate organic fraction was determined using the modified Mebius method in digestion tubes (Nelson and Sommers, 1982).

Potential C mineralization of the particulate organic fraction was determined from a 1.5- to 11.5-g subsample, depending on availability of material, in a vial placed in a 1-L canning jar along with vials containing 10 mL of 0.2 *M* NaOH to trap evolved CO_2 and water to maintain high humidity. Soil was moistened to ≈50% water content (w/w) and incubated at 25°C for 24 d. Alkali traps were replaced at 3 and 10 d and the quantity of CO_2–C evolved determined by titration with HCl at 3, 10, and 24 d (Anderson, 1982). Basal mineralization of POC was estimated as the rate of CO_2–C evolved from 10 to 24 d, since ≥90% of the flush of CO_2–C following rewetting was previously found to occur prior to 10 d (Franzluebbers et al., 1996). Potential C mineralization of whole soil was determined similar to that described for the particulate organic fraction, except a 40-g subsample was wetted to field capacity (0.25, 0.3, 0.3, and 0.4 kg water kg^{-1} soil for the loam, silt loam, clay loam, and clay, respectively) (Franzluebbers and Arshad, 1996a,b). Specific POC mineralization was calculated as the rate of basal mineralization of POC per unit of POC. Specific whole-soil mineralization was calculated as the rate of basal soil mineralization per unit of SOC.

Standing stock of POC, the fraction of whole-SOC as POC, basal mineralization of POC, specific mineralization of POC, and the ratio of specific POC mineralization to specific whole-soil mineralization were analyzed for each soil depth separately, with tillage regime as a split plot within soil type/site using the general linear model procedure of SAS (SAS Institute, 1990). Tillage means were used in regressions to determine clay content effects. The effects of tillage regime and clay content were considered significant at $P \leq 0.1$.

RESULTS AND DISCUSSION

Particulate organic C concentration averaged 14.6 ± 4.3 g kg^{-1} soil at the 0- to 50-mm depth, 9.8 ± 3.7 g kg^{-1} soil at the 50- to 125-mm depth, and 4.8 ± 1.5 g kg^{-1} at the 125- to 200-mm depth (mean ± standard deviation of four soils). Standing stock of POC under ZT was 20 ± 10% greater than under CT at a depth of 0 to 50 mm and was little affected by tillage at lower depths, except in the silt loam and clay loam at the 50- to 125-mm depth (Table 2). Accumulation of this "slow" pool of SOC (Parton et al., 1987; Cambardella and Elliott, 1992) near the soil surface suggests its derivation from recent plant root and residue additions. Cambardella and Elliott (1992) found this material to be composed mostly of root fragments in various stages of decomposition in a grassland soil, with 13 to 31% derived from plant material added within the past 20 yr.

The portion of SOC as POC decreased with depth in all soils (Table 2). The readily mineralizable fraction of whole-SOC also decreased with depth (Franzluebbers and Arshad, 1996a,b), suggesting that SOC, as a result of less POC, became more "passive" with depth. The portion of SOC as POC was 13 ± 14% greater (mean ± standard deviation of four soils) under ZT than under CT at a depth of 0 to 50 mm, indicating that surface

Table 1. Site and experimental conditions of the four field studies.

Property	Donnelly loam	Donnelly silt loam	Hythe clay loam	Falher clay
Location	55°42′ N, 120°10′ W	55°46′ N, 120°21′ W	55°11′ N, 119°32′ W	55°43′ N, 118°41′ W
Soil classification (USDA)	coarse-loamy, mixed, frigid Typic Cryoboralf	fine-loamy, mixed, frigid Typic Cryoboralf	fine, montmorillonitic, frigid Mollic Cryoboralf	fine, montmorillonitic, frigid Typic Natriboralf
Soil organic C, kg m^{-2} 0.2 m^{-1}	4.3	5.1	6.8	8.2
Clay, %, 0–0.2-m depth	18	28	37	63
Silt, %, 0–0.2-m depth	46	51	41	31
pH (1:2 soil/water)	6.6	5.5	6.7	5.7
Initiation of tillage regime	1988	1979	1991	1989
Crop sequence (crop previous to sampling in 1995 is underlined)	<u>wheat</u>–canola–barley	<u>barley</u>	<u>barley</u>–canola–barley	barley–fallow–<u>canola</u>–wheat
Experimental design	paired plots in adjacent fields	paired plots in adjacent fields	randomized, block	randomized, block
Plot size, m	20 by 50	20 by 50	3 by 15	12 by 39
Replications	4	3	4	4

Table 2. Standing stock of particulate organic C, fraction of soil organic C as particulate organic C, standing stock of basal mineralization of particulate organic C, and the ratio of specific particulate organic C mineralization to specific whole-soil organic C mineralization as affected by soil type, depth, and tillage regime (CT is conventional tillage and ZT is zero tillage).

Soil	0 to 50 mm			50 to 125 mm			125 to 200 mm		0 to 200 mm		
	CT		ZT	CT		ZT	CT	ZT	CT		ZT
						Particulate organic C, kg m^{-2}					
Donnelly loam	0.53		0.58	0.74		0.66	0.51	0.47	1.79		1.71
Donnelly silt loam	0.78	**	0.90	0.97	†	0.81	0.53	0.49	2.27		2.20
Hythe clay loam	0.74	***	0.93	1.13	**	1.33	0.67	0.54	2.54†		2.80
Falher clay	0.48	***	0.63	0.60		0.63	0.21	0.32	1.29†		1.59
Mean	0.63	***	0.76	0.86		0.86	0.48	0.45	1.97		2.07
						Fraction of soil organic C as particulate organic C, g kg^{-1}					
Donnelly loam	0.49		0.52	0.42	*	0.38	0.35	0.33	0.41		0.40
Donnelly silt loam	0.49	†	0.56	0.43		0.40	0.38	0.36	0.43		0.44
Hythe clay loam	0.44		0.44	0.39		0.40	0.35	0.29	0.39		0.39
Falher clay	0.21	*	0.28	0.18		0.19	0.08	0.12	0.16	†	0.19
Mean	0.40	*	0.45	0.35		0.34	0.29	0.28	0.35		0.35
						Basal mineralization of particulate organic C, g CO_2–C m^{-2} d^{-1}					
Donnelly loam	0.17		0.22	0.21		0.21	0.13	0.12	0.51		0.54
Donnelly silt loam	0.66	**	1.37	0.56		0.43	0.19	0.16	1.42	†	1.96
Hythe clay loam	0.58		0.48	0.58	†	0.78	0.26	0.22	1.42		1.48
Falher clay	0.32		0.38	0.46		0.52	0.17	0.25	0.95		1.15
Mean	0.43	*	0.61	0.45		0.48	0.19	0.18	1.07		1.28
						Ratio of specific particulate organic C mineralization to specific whole-soil organic C mineralization					
Donnelly loam	0.17		0.33	0.57		0.85	0.89	0.95	0.36	*	0.59
Donnelly silt loam	0.78	*	1.37	0.86		1.00	0.53	0.66	0.77	*	1.23
Hythe clay loam	0.63		0.67	1.14	†	1.72	0.99	1.23	0.87		1.13
Falher clay	1.12		0.89	2.63	**	3.69	4.79	4.14	2.15		2.16
Mean	0.67		0.81	1.30	**	1.82	1.80	1.75	1.04	*	1.28

†,*,**, and ** between tillage means within soil type and depth indicate significance at $P \leq 0.1$, 0.05, 0.01, and 0.001, respectively.

placement of crop residues could increase the fraction of this "slow" pool of SOC at the soil surface, in addition to the more "active" pools as indicated by the data from Carter and Rennie (1982) and Doran (1987). The fraction of SOC as POC (0.16–0.44) in these forest-derived agricultural soils from Alberta and British Columbia was higher than that in cultivated soils from Nebraska (0.18–0.25; Cambardella and Elliott, 1992) and Saskatchewan (0.08–0.13; Tiessen and Stewart, 1983), but similar to that of those soils under native grassland vegetation (0.20–0.39). Agricultural soils from Kentucky and Indiana (Elliott et al., 1994) and from Pennsylvania (Wander et al., 1994) had ratios of POC to SOC ranging from 0.07 to 0.19. In cited studies, soil was passed through a 2-mm screen and residues removed; however, we did not remove residues during sieving through a 5.6-mm screen. In addition, the colder and drier climate in northern Alberta and British Columbia compared with the warmer and wetter climates of the cited studies may have been more limiting to the decomposition of recent organic matter inputs, resulting in greater accumulation of POC.

The pool of POC was 5 to 16 times greater than the pool of floating organic C collected during a wet-sieving procedure from these same four soils (Franzluebbers and Arshad, 1996c). The pool of organic C floating in water had a similar C concentration (237 ± 25 g kg^{-1}) and represented a similar portion of SOC (5 ± 3%) as the light fraction (<1.7 Mg m^{-3}) isolated from long-term cropping systems in Saskatchewan (Janzen et al., 1992). Although it has been suggested that the pool size and characteristics of POC may be similar to those of light-fraction SOC (Cambardella and Elliott, 1992; Wander et al., 1994), our results would indicate that POC (determined by size) is a larger pool of SOC that is composed of light and somewhat heavier density SOC than light-fraction SOC (determined by density). This conclusion is supported by the findings of Cambardella and Elliott (1992) and Hassink (1995b), who reported that approximately two-thirds of POC had a density of 1.4 to 1.9 Mg m^{-3}.

Basal mineralization of POC at a depth of 0 to 50 mm was twice as high under ZT than under CT in the silt loam and was 42% greater under ZT than under CT when averaged across soils (Table 2). In general, there was no difference in basal mineralization of POC between tillage regimes below the surface depth, except for 34% greater mineralization under ZT than under CT in the clay loam at a depth of 50 to 125 mm.

When normalized to the amount of POC present, specific mineralization of POC was greater under ZT than CT only in the silt loam at a depth of 0 to 50 mm (data not shown). Cumulative specific mineralization of POC to a depth of 200 mm indicated a similar tillage effect in the silt loam (Fig. 1). The silt loam was managed under ZT longer (16 yr) than soils at other locations, suggesting that although tillage affected the quantity of POC in a relatively short time (Table 2), alteration of the quality of POC may occur only after an extended period of time in this cold semiarid environment.

Specific mineralization of POC was not significantly affected by soil texture at a depth of 0 to 50 mm, but increased with increasing clay content at depths of 50 to 125 and 125 to 200 mm (Fig. 2). Hassink (1995a) reported that specific mineralization of POC was unaffected by texture from three Dutch grassland soils sam-

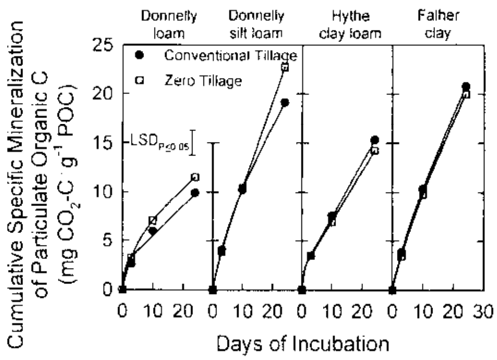

Fig. 1. Cumulative specific mineralization of particulate organic C at 0- to 200-mm depth as affected by soil type and tillage regime.

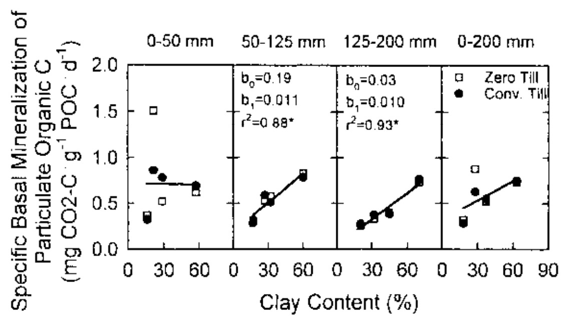

Fig. 2. Specific basal mineralization of particulate organic C as affected by clay content, soil depth, and tillage regime. Only regressions that were significant ($P \leq 0.1$) are described.

pled to a depth of 100 mm. Our results suggest that specific mineralization of POC can be affected by textural differences at depths below the direct influence of surface residues.

The ratio of specific POC mineralization to specific whole-SOC mineralization was greater under ZT than under CT in the silt loam at a depth of 0 to 50 mm and averaged across soils at a depth of 50 to 125 mm (Table 2). However, specific whole-SOC mineralization was lower under ZT than under CT in all soils at a depth of 50 to 125 mm (Franzluebbers and Arshad, 1996a,b). A larger standing stock of POC near the soil surface combined with greater potential decomposability of POC (i.e., lower in situ decomposition) would suggest that ZT management may have increased the residence time of the POC pool. This may have been due to greater fluctuations in moisture and temperature at the soil surface where POC was concentrated under ZT that decreased opportunities for in situ decomposition.

The ratio of specific POC mineralization to specific whole-SOC mineralization at a depth of 0 to 200 mm increased linearly with clay content ($r = 0.96$, $n = 8$; Table 2), due to increasing specific POC mineralization (Fig. 2) and decreasing specific whole-SOC mineralization (Franzluebbers and Arshad, 1996a,b) with increasing clay content. This result, combined with a strong positive relationship between clay content and macroaggregation (Franzluebbers and Arshad, 1996c), suggests that POC may have been physically protected within macroaggregates during whole-soil incubations, but rendered more mineralizable once the POC was released from protection by macroaggregation following dispersion.

Specific mineralization of POC in these soils indicated that POC has turnover characteristics that are similar to the intermediate- to heavy-density fractions of POC reported by Hassink (1995a). When the data presented by Hassink (1995a) was converted to units in this presentation, specific mineralization of light POC (<1.1 Mg m^{-3}) was 2.3 g kg^{-1} d^{-1}, of intermediate POC (1.1–1.4 Mg m^{-3}) was 1.0 g kg^{-1} d^{-1}, of heavy POC (>1.4 Mg m^{-3}) was 0.4 g kg^{-1} d^{-1}, and from whole-SOC was 0.1 g kg^{-1} d^{-1} in Dutch grassland soils (Hassink, 1995a). These descriptions of the turnover characteristics of POC, the "slow" pool of SOC, could lead to refinements in models of soil organic matter turnover.

SUMMARY AND CONCLUSIONS

Tillage management had an influence on the standing stock and specific mineralization of POC only to a depth of 125 mm. Changes in POC due to ZT in this cold semiarid climate appeared to be uncoupled with the lack of changes observed in more active SOC pools in these same soils, but were similar to tillage-induced changes in active and total SOC pools in more temperate climates. Standing stock of POC was greatest in a medium-textured soil. The fraction of SOC as POC decreased from 0.41 in a coarse-textured soil to 0.16 in a fine-textured soil. The quantity of POC changed due to tillage before measurable changes in the quality of POC could be detected. Particulate organic C was less mineralizable than whole-SOC in coarse-textured soil, but was several times more mineralizable in fine-textured soil. Particulate organic C, therefore, may be of greater importance for defining SOC turnover in coarse-textured soils in this cold semiarid climate, similar to aggregate protection mechanisms proposed for SOC turnover in fine-textured soils. The POC fraction was easily separated from whole soil, making it a procedurally definable fraction that could be used to better characterize the potential turnover of specific components of soil organic matter.

ACKNOWLEDGMENTS

This study was funded in part under the Canada–Alberta Environmentally Sustainable Agriculture Agreement.

REFERENCES

Anderson, J.P.E. 1982. Soil respiration. p. 837–871. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Cambardella, C.A., and E.T. Elliott. 1992. Particulate soil organic-matter changes across a grassland cultivation sequence. Soil Sci. Soc. Am. J. 56:777–783.

Carter, M.R., and D.A. Rennie. 1982. Changes in soil quality under zero tillage farming systems: Distribution of microbial biomass and mineralizable C and N potentials. Can. J. Soil Sci. 62:587–597.

Collins, H.P., P.E. Rasmussen, and C.L. Douglas, Jr. 1992. Crop rotation and residue management effects on soil carbon and microbial dynamics. Soil Sci. Soc. Am. J. 56:783–788.

Dalal, R.C., and R.J. Mayer. 1986. Long-term trends in fertility of soils under continuous cultivation and cereal cropping in southern Queensland. III. Distribution and kinetics of soil organic carbon in particle-size fractions. Aust. J. Soil Res. 24:281–292.

Doran, J.W. 1987. Microbial biomass and mineralizable nitrogen distributions in no-tillage and plowed soils. Biol. Fertil. Soils 5:68–75.

Doran, J.W., D.C. Coleman, D.F. Bezdicek, and B.A. Stewart (ed.). 1994. Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA and ASA, Madison, WI.

Elliott, E.T., I.C. Burke, C.A. Monz, S.D. Frey, K.H. Paustian, H.P. Collins, E.A. Paul, C.V. Cole, R.L. Blevins, W.W. Frye, D.J. Lyon, A.D. Halvorson, D.R. Huggins, R.F. Turco, and M.V. Hickman. 1994. Terrestrial carbon pools in grasslands and agricultural soils: Preliminary data from the Corn Belt and Great Plains regions. p. 179–191. *In* J.W. Doran et al. (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA and ASA, Madison, WI.

Franzluebbers, A.J., and M.A. Arshad. 1996a. Soil organic matter pools during early adoption of conservation tillage in northwestern Canada. Soil Sci. Soc. Am. J. 60:1422–1427.

Franzluebbers, A.J., and M.A. Arshad. 1996b. Soil organic matter pools with conventional and zero tillage in a cold, semiarid climate. Soil Tillage Res. 39:1–11.

Franzluebbers, A.J., and M.A. Arshad. 1996c. Water-stable aggregation and organic matter in soils under conventional and zero tillage. Can. J. Soil Sci. 76:387–393.

Franzluebbers, A.J., R.L. Haney, F.M. Hons, and D.A. Zuberer. 1996. Determination of microbial biomass and nitrogen mineralization following rewetting of dried soil. Soil Sci. Soc. Am. J. 60:1133–1139.

Franzluebbers, A.J., F.M. Hons, and D.A. Zuberer. 1994. Long-term changes in soil carbon and nitrogen pools in wheat management systems. Soil Sci. Soc. Am. J. 58:1639–1645.

Gee, G.W., and J.W. Bauder. 1986. Particle-size analysis. p. 383–411. *In* A. Klute (ed.) Methods of soil analysis. Part 1. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Gregorich, E.G., R.G. Kachanoski, and R.P. Voroney. 1989. Carbon mineralization in soil size fractions after various amounts of aggregate disruption. J. Soil Sci. 40:649–659.

Gupta, V.V.S.R., P.R. Grace, and M.M. Roper. 1994. Carbon and nitrogen mineralization as influenced by long-term soil and crop residue management systems in Australia. p. 193–200. *In* J.W. Doran et al. (ed.) Defining soil quality for a sustainable environment. SSSA Spec. Publ. 35. SSSA and ASA, Madison, WI.

Hassink, J. 1995a. Decomposition rate constants of size and density fractions of soil organic matter. Soil Sci. Soc. Am. J. 59:1631–1635.

Hassink, J. 1995b. Density fractions of soil macroorganic matter and microbial biomass as predictors of C and N mineralization. Soil Biol. Biochem. 27:1099–1108.

Janzen, H.H., C.A. Campbell, S.A. Brandt, G.P. Lafond, and L. Townley-Smith. 1992. Light-fraction organic matter in soils from long-term crop rotations. Soil Sci. Soc. Am. J. 56:1799–1806.

Nelson, D.W., and L.E. Sommers. 1982. Total carbon, organic carbon, and organic matter. p. 539–594. *In* A.L. Page et al. (ed.) Methods of soil analysis. Part 2. 2nd ed. Agron. Monogr. 9. ASA and SSSA, Madison, WI.

Parton, W.J., D.S. Schimel, C.V. Cole, and D.S. Ojima. 1987. Analysis of factors controlling soil organic matter levels in Great Plains grasslands. Soil Sci. Soc. Am. J. 51:1173–1179.

SAS Institute. 1990. SAS user's guide: Statistics. Version 6 ed. SAS Inst., Cary, NC.

Tiessen, H., and J.W.B. Stewart. 1983. Particle-size fractions and their use in studies of soil organic matter: II. Cultivation effects on organic matter composition in size fractions. Soil Sci. Soc. Am. J. 47:509–514.

Wander, M.M., S.J. Traina, B.R. Stinner, and S.E. Peters. 1994. Organic and conventional management effects on biologically active soil organic matter pools. Soil Sci. Soc. Am. J. 58:1130–1139.